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14. ABSTRACT

The data obtained during this award period provide comparative measurements of underwater and aerial hearing sensitivity in pinnipeds and the effects of exposure to underwater and aerial noise. Much greater aerial sensitivity than previously documented in pinnipeds was demonstrated in individuals from three species. These data were obtained in a highly controlled acoustic testing environment and suggest that most, if not all, previous aerial pinniped audiograms were noise limited. Similar simultaneous (masking) and residual (auditory fatigue) effects of noise exposure were demonstrated in air and water. Noise exposure in the auditory fatigue experiments was systematically varied in both exposure level and exposure duration to investigate the relative importance of these noise parameters in causing temporary changes in hearing sensitivity. Age-related changes in hearing were also demonstrated and indicated most severe hearing losses at relatively high test frequencies. The combined results have a number of practical and theoretical implications and, most notably, indicate that pinniped cochlear processes are similar both in air and water to those occurring in terrestrial mammals.

15. SUBJECT TERMS

pinniped, bioacoustics, auditory fatigue, temporary threshold shift, masking, psychophysics

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FINAL REPORT

GRANT #: N00014-99-1-0164

PRINCIPAL INVESTIGATOR: Dr. Ronald J. Schusterman

INSTITUTION: University of California, Santa Cruz

GRANT TITLE: Pinniped bioacoustics: auditory mechanisms, temporary threshold shift, and effects of noise on signal reception

AWARD PERIOD: 1 October 1998 - 30 September 2001

OBJECTIVE: To investigate amphibious hearing mechanisms in three pinniped species [northern elephant seal (*Mirounga angustirostris*), harbor seal (*Phoca vitulina*), and California sea lion (*Zalophus californianus*)]; to measure the simultaneous (masking) and residual (auditory fatigue) effects of noise exposure on underwater and aerial hearing in these species; to relate these laboratory findings to field studies of pinniped acoustic communication.

APPROACH: Behavioral hearing thresholds are obtained from trained pinnipeds, using standard signal detection paradigms and psychophysical testing procedures. Thresholds are measured at a range of frequencies and under a variety of conditions. Underwater hearing thresholds are obtained at a depth of 1 m in an acoustically mapped, circular, 7.5 m diameter tank. Aerial hearing thresholds are obtained in a DURIP-funded sound attenuating hemi-anechoic chamber, which affords a highly controlled acoustic environment. In a series of related experiments, comparable underwater and aerial hearing thresholds are determined under the following conditions: 1) in the relative absence of interfering noise (absolute hearing sensitivity), 2) in the presence of simultaneous masking noise (auditory masking), and 3) following exposure to fatiguing noise (temporary threshold shift (TTS)). Permanent threshold shift (PTS) is documented by investigating age-related changes in hearing sensitivity.

The results of the laboratory audiometric studies are integrated with measurements of ambient noise and estimates of vocalization source levels collected on pinniped rookeries. These data are applied to a source-path-receiver model to estimate average signal detection ranges for biological signals in a variety of natural masking noise conditions.

ACCOMPLISHMENTS: The investigations of amphibious hearing have yielded complete audiometric profiles (audiograms) for all three pinniped species. The aerial audiograms obtained for all three species under highly controlled conditions show much greater sensitivity than has been previously measured. Best frequency sensitivity was from 2 kHz to 12 kHz for the harbor seal and the California sea lion. Corresponding absolute sensitivities were approximately 0 dB re: 20μPa, which is similar to those measured in some of the most sensitive terrestrial mammals tested in comparable conditions. The deep diving northern elephant seal showed best frequency sensitivity at lower frequencies (0.3 to 1.6 kHz), with best absolute sensitivity at least 25 dB inferior to the best sensitivities measured for the harbor seal and California sea lion.

The phenomenon of age-related PTS was evaluated by measuring the underwater and aerial hearing sensitivity of a 25-year-old California sea lion and comparing her hearing to that of a younger sea lion, as well as to the same sea lion tested 23 years earlier. The results showed hearing losses of 10-50 dB in the older animal, regardless of the media, with the greatest hearing losses occurring at the highest frequencies (>6.4 kHz).

The effect of simultaneous noise on hearing was evaluated for each species in a task that required the trained subjects to detect signals embedded in background noise. Aerial and underwater masked hearing thresholds were determined for various frequencies between 200 Hz and 8 kHz (which includes the range of many low frequency anthropogenic noise sources). Aerial critical ratios (the amount by which the masked thresholds exceed the masking noise spectral density levels) for each subject generally increased with increasing frequency in a manner similar to that observed in most other mammals. Critical ratio magnitudes at identical test frequencies were essentially the same in air and water for each subject.

The research effort placed particular emphasis on examining auditory fatigue, or TTS, in pinnipeds. A series of underwater and aerial experiments were designed to evaluate how threshold shifts change as a function of noise exposure level and duration and what differences, if any, exist between the effects of underwater or aerial fatiguing noise. As previously reported, reliable threshold shifts were obtained for a northern elephant seal, a harbor seal, and a California sea lion following 22 min. net noise exposure to octave-band noise 65 dB above each subject's absolute hearing threshold (65 dB sensation level (SL)). Average TTS magnitudes for this exposure condition ranged from 4.6 to 4.9 dB. When the exposure level was increased to 80 dB SL and the exposure duration maintained at 22 min., average threshold shifts following noise exposure ranged from 2.9 to 4.8 dB. When the exposure level was increased to 95 dB SL for similar exposure duration (25 min. net exposure), average threshold shifts for the same subjects ranged from 2.5 to 6.5 dB. However, for the 95 dB SL exposure condition, increasing exposure duration to a 50 min. net time period generally resulted in larger average threshold shifts, ranging from 3.4 to 12.2 dB. Thus, increasing noise exposure duration (for one exposure level) resulted in greater increases in measured TTS than did increasing exposure levels for similar exposure durations.

Throughout the various phases of underwater TTS testing, control sequences were conducted in which all phases of testing were completed, but no noise was projected during a mock exposure phase. Data from control sequences did not indicate any consistent differences in hearing associated with completing the sequence of tasks involved in obtaining the TTS data. This indicates that the threshold shifts obtained in each noise exposure condition was attributable to the presence of the fatiguing noise and not some other factors, such as changes in attention or motivation. We also tested for temporary hearing losses ½-octave above the center frequency of the noise exposure band in several of the underwater exposure conditions. While maximal TTS values have been observed at this relative frequency for some other mammals, threshold shifts for the pinnipeds in this study were consistently smaller at frequencies ½-octave above than at the center frequency of the noise exposure band.

There were two primary constraints in interpreting the underwater TTS results. First, noise fields were relatively variable over small distances within the tank and second, subjects periodically returned to the surface to breathe during noise exposure. The later was the more important, because it resulted in variable intermittence within the ''continuous'' noise exposure phase. These limitations were predominately overcome by testing the subjects within the hemi-anechoic test chamber. An additional reason for conducting aerial TTS experiments was that comparative underwater and aerial data could further clarify pinniped auditory mechanisms. In the most recent study, aerial TTS was measured in the harbor seal subject following exposure to 95 dB SL octave band noise for 50 minutes net duration, during which intermittence similar to that experienced for underwater testing was intentionally introduced into aerial noise exposure. The threshold shifts for this subject measured in these conditions in air were comparable to those obtained under water in very similar relative exposure conditions.

Minimum and maximum signal detection ranges (*i.e.*, estimated communicative distances between sender and receiver seals) in natural noise were estimated based on integrated laboratory audiometric and acoustic measurements made in a northern elephant seal breeding colony. The results indicated that signal detection ranges can differ by more than an order of magnitude in natural masking noise conditions.

CONCLUSIONS: The most recent absolute underwater hearing data were consistent with those previously obtained. However, the aerial audiograms indicated significantly greater sensitivity than previously reported for any pinniped species. The lower measured thresholds reflect the superior ambient noise control afforded by the testing chamber. These findings suggest that most, if not all, previous aerial pinniped audiograms were noise limited.

The age-related differences in aerial hearing sensitivity, along with our earlier results in water, were the first demonstrations of PTS in a pinniped species. The frequency-specific pattern of hearing loss observed supports the notion that cochlear mechanisms operating in the pinniped auditory system are similar to those of terrestrial mammals.

The finding that critical ratios were not significantly different in air and water for individuals with quite different unmasked aerial and underwater hearing sensitivity supports the idea that the simultaneous effects of noise exposure result from signal interference within the cochlea. Additionally, this finding provides justification for considering all available pinniped masking data irrespective of the medium in which they were obtained (*i.e.* aerial and underwater critical ratio data may be pooled).

The underwater TTS experiments provided comparative auditory fatigue data within individual subjects following noise exposure of variable level and duration. When the increases were considered simply in terms of sound pressure level and net exposure duration, the results did not seem to indicate an equal energy relationship between increases in these parameters and TTS magnitude. However, we addressed this matter more directly by converting the exposure level and duration measurements into energy flux density values, accounting for the intermittence of noise exposure. Following these conversions, there was a relatively linear relationship between increases in noise energy flux density and increases in measured auditory fatigue for two of the three pinniped subjects. The ongoing aerial TTS experiments in which noise exposure level and duration are systematically varied under highly controlled conditions will clarify our understanding of how these variables interact to cause pinniped TTS. Therefore, the equal energy hypothesis may indeed be predictive of pinniped TTS. Based on the available data, maximal threshold shift occurred at the frequency corresponding to the center of the noise exposure band rather than ½-octave higher. However, more data on this issue are required to arrive at a firm conclusion. The initial aerial TTS results for one individual indicate that similar magnitude TTS occurs following aerial and underwater noise of identical relative exposure level, duration, and intermittence. This suggests that auditory fatigue in pinnipeds is also the result of cochlear phenomena and provides further justification for conducting the definitive pinniped TTS experiments in air with variable level and duration noise within the highly controlled conditions of the hemi-anechoic chamber. Thus, all of the comparative data obtained on the impacts of noise on hearing support the hypothesis that pinniped cochlear mechanisms are fundamentally similar between media, and are similar to those occurring in other terrestrial mammals, including humans.

Finally, the communicative range estimates for northern elephant seals provided some first-order estimates of how variable noise conditions affect signal detection, and illustrate the utility of integrating laboratory and field bioacoustic data. Additionally, these data provide a model that can be used to predict specific anthropogenic noise impacts on acoustic communication in this species.

SIGNIFICANCE: The data obtained during this award period provide comparative measurements of pinniped underwater and aerial hearing sensitivity and how their hearing is affected by noise. The results have a number of practical implications regarding free-ranging pinnipeds and anthropogenic noise exposure, as well as implications for the design of future laboratory audiometric and field bioacoustic research. The findings are significant in terms of our understanding of pinniped auditory mechanisms. Results show that pinniped cochlear processes are similar to those occurring in terrestrial mammals and that a variety of noise impacts on pinniped hearing are similar under water and in air. Therefore, models based on the results of highly controlled aerial noise exposure experiments can be used to predict the effects of underwater noise exposure on pinniped hearing.

PATENT INFORMATION: N/A

AWARD INFORMATION:

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Colleen Reichmuth Kastak, University of California, Santa Cruz: Ocean Sciences GAANN Fellowship, 2000-2002

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